LEARNING OBJECTIVES:

1.11.01 Identify the four basic methods for minimizing personnel external exposure.

1.11.02 Using the Exposure Rate = 6CEN equation, calculate the gamma exposure rate for specific radionuclides.

1.11.03 Identify "source reduction" techniques for minimizing personnel external exposures.

1.11.04 Identify "time-saving" techniques for minimizing personnel external exposures.

1.11.05 Using the stay time equation, calculate an individual's remaining allowable dose equivalent or stay time.

1.11.06 Identify "distance to radiation sources" techniques for minimizing personnel external exposures.

1.11.07 Using the point source equation (inverse square law), calculate the exposure rate or distance for a point source of radiation.

1.11.08 Using the line source equation, calculate the exposure rate or distance for a line source of radiation.

1.11.09 Identify how exposure rate varies depending on the distance from a surface (plane) source of radiation.

1.11.10 Identify the definition of "mass attenuation coefficient" and "linear attenuation coefficient".

1.11.11 Identify the definition of "density thickness".

1.11.12 Identify the density-thickness values, in mg/cm^2, for the skin, the lens of the eye and the whole body.

1.11.13 Calculate shielding thickness or exposure rates for gamma/x-ray radiation using the equations.

INTRODUCTION

The goal of any radiation safety program is to reduce exposure, whether internal or external, to a minimum. The external exposure reduction and control measures available are of primary importance to the everyday tasks performed by the RCT. In this lesson, we will address the DOE and Facility Administrative Exposure limits and the basic methods used for reducing radiation exposure. Various techniques such as time, distance, and shielding that are used to help reduce external exposure controls will be discussed. These techniques are useful to maintain personnel exposure below administrative and federal limits.

BASIC METHODS FOR EXPOSURE REDUCTION

The goal of radiological control is embodied in the acronym "ALARA" which stands for As Low As Reasonably Achievable.

The Radiological Control organization shall make whatever reasonable efforts it can to reduce exposure to the lowest levels, taking into account economic and practical considerations.

1.11.01 Identify the four basic methods for minimizing personnel external exposure.

There are four basic methods available to reduce external exposure to personnel:

- **Reduce** the amount of **source** material (or reduce emission rate for electronically-generated radiation).
- Reduce the amount of **time** of exposure to the source of radiation.
- Increase the **distance** from the source of radiation.
- Reduce the radiation intensity by using **shielding** between the source and personnel.

EXPOSURE RATE DETERMINATION

In order to use the basic methods for controlling exposure, the technician must be able to determine the intensity of the radiation fields. The following equations are used to make this determination.

1.11.02	*Using the Exposure Rate = 6CEN equation, calculate the gamma exposure rate for specific radionuclides.*

A "rule-of-thumb" method to determine the radiation field intensity for simple sources of radioactive material is the *curie/meter/rem* rule.

1 Ci @ 1 meter = 1 R/hr

This thumb rule only applies to Cobalt-60. For other gamma emitters another equation can be used to estimate the dose rate at 1 foot or 1 meter.

To determine the gamma radiation field intensity (**I**) *in R/hr* at one foot from a radioactive point source use the following equation:

$$I_{1ft} = 6CEN$$

where:

C = source activity *in Curies* (Ci)
E = gamma energy *in MeV*
N = number of gammas per disintegration (photon yield)

1) Accurate to within ±20% for gamma energies between 0.05 MeV and 3 MeV.
2) If N is not given, assume 100% photon yield (1.00 photons/disintegration).
3) If more than one photon energy is given, take the sum of each photon multiplied by its percentage, i.e.
$[(\gamma_1)(\%_1) + (\gamma_2)(\%_2) + \cdots + (\gamma_n)(\%_n)]$.

For distances given in meters the equation may be written as:

$$I_{1m} = 0.5CEN$$

For short distances greater than 1 foot from the source, the inverse square law can be applied with reference to the dose rate at 1 foot, resulting in the following equation:

$$I = \frac{(6CEN)(1^2)}{d^2}$$

where: **d** = distance in feet;

For metric distances the equation becomes:

$$I = \frac{(0.5CEN)(1^2)}{d^2}$$

where: **d** = distance in meters

Example:

Determine the exposure rate at 10 ft for a 8 Ci point source of CO^{60} that emits a 1.173 and 1.332 MeV gamma, both at 100% of the disintegrations.

$$I\ at\ 10ft = \frac{[(6)(8)(\Sigma 1.173(1) + 1.332(1))][1^2]}{(10\ ft)^2} = 1.2\ R/hr$$

Sample Problem 1.11-1

Determine the exposure rate at 1 ft for a 1-Ci point source of Cesium-137 that emits a 662 keV gamma in 85% of the disintegrations.

Sample Problem 1.11-2

Estimate the exposure rate at 2 meters from a 1.8 Ci point source of ^{60}Co that emits two gammas (1.173 MeV and 1.332 MeV) for every disintegration.

Sample Problem 1.11-3

Calculate the exposure rate at 1 foot for a 400-mCi ^{192}Ir which emits the following gammas: 0.316 MeV (87%), 0.486 MeV (52%), 0.308 MeV (32%), 0.295 MeV (30%).

Note: Ir-192 emits other gammas at lower percentages, but these are not included.

SOURCE REDUCTION

1.11.03	*Identify "source reduction" techniques for minimizing personnel external exposures.*

The first method that should be employed to reduce personnel external exposure is source reduction. If a source can be eliminated or if its hazard potential can be significantly reduced, then other engineering means may not be necessary.

Various techniques are employed to accomplish external exposure reduction using source reduction.

Allow natural decay to reduce source strength

If the radioisotopes involved are short-lived, then waiting to perform the task may significantly reduce the hazard.

Move the source material to another location

- Decon the equipment or material through mechanical or chemical means to remove the source material prior to working in the area or on the equipment.
- Reduce the source material in the system by flushing equipment with hot water or chemical solutions and collect it in a less frequently occupied area.
- Discharge or remove the resin or filtering media prior to working in the area or on the system.
- Move the radioactive source (e.g., a drum, barrel or calibration source) to another location prior to starting work.

Sample Problem 1.11-4

A contaminated system pump has been replaced with a rebuilt pump and the replaced pump must be rebuilt prior to the next replacement. Assume the 1 Ci mixture of radionuclides contained in the pump has a half-life of 40 days. In 80 days what would the original activity in the pump be reduced to?

By waiting for natural decay to reduce the source strength, a considerable savings in external exposure can be achieved.

TIME SAVINGS

1.11.04 Identify "time-saving" techniques for minimizing personnel external exposures.

Personnel working in radiation fields must limit their exposure time so that they do not exceed their established permissible dose limits and are able to keep exposures ALARA. The longer the time spent in the radiation field, the greater the exposure to the individual; therefore, the amount of time spent in radiation fields should be reduced. The Radiological Control Technician needs to be aware that radiation exposures are directly proportional to the time spent in the field. If the amount of time is doubled, then the amount of exposure received is doubled. Various techniques are employed to reduce personnel external exposure by reducing the amount of time spent in radiation fields:

- Analyze and train using **mock-ups** of the work site. A particular task can be analyzed on a mock-up of the system to determine the quickest and most efficient method to perform the task. The team of workers assigned to the task can rehearse, without radioactive materials, so that problems can be worked out and the efficiency of the team increased prior to any exposure. By determining the most efficient method and rehearsing the task, the amount of time, and therefore the exposure, can be reduced.

- Use of **pre-job briefings** is an important part of any good ALARA program. Discussions at the pre-job briefing with the individuals assigned to the task can identify any potential problems not previously identified. Identifying personnel responsibilities and the points at which various individuals are required to be present can reduce the overall time required to perform the job.

- **Review job history** files. Review the files from previously completed tasks of the same nature to identify previous problems and spots where time could be saved.

- **Pre-stage all tools and equipment**. All tools should be staged prior to entry to prevent the worker from waiting in a radiation field for a tool to arrive by messenger or helper.

- **Pre-assemble equipment and tools outside the area**. Equipment that can be preassembled should be preassembled prior to any entry into the radiation field. Tools that require assembly, pre-testing, and/or calibration should be performed outside the radiation field.

- Use **time-limiting devices**. Time limitations for workers can be monitored and limited using various devices such as stopwatches, alarming dosimeters, or radio-transmitting dosimeters.

- Use **communication devices** such as walkie-talkies. Poor communication can lead to incorrect or poor quality work and prolonged waiting in the radiation field while supervisors or experts are contacted. Communication devices such as walkie-talkies or radio headsets can alleviate these problems and reduce the amount of time that is spent in the radiation field.

- Use a **team of workers** instead of allowing one individual to receive all of the exposure. Even if a task requires a minimum amount of time, if it would cause one individual to receive an exposure greater than allowable, a team of workers should be used to reduce the individual exposures. If a team of workers is used, good communications are necessary to ensure the total exposure for the job does not increase significantly.

- Use **experienced personnel**. The total time required to perform a job is reduced if experts are used instead of inexperienced personnel. Inexperienced personnel should not be trained in significant radiation fields.

1.11.05 Using the stay time equation, calculate an individual's remaining allowable dose equivalent or stay time.

The exposure received by personnel will increase as the time spent in the radiation field increases. The exposure received (X) is equal to the radiation field intensity times the exposure time, or:

$$X = \left(\frac{R}{t}\right)T$$

where:

$\frac{R}{t}$ = *dose rate*

T = *length of time exposed*

Sample Problem 1.11-5

A worker is performing valve maintenance in a 120 mR/hr gamma radiation field and expects the work to take 90 minutes. What will his total exposure be for the job?

When the time allowed in a radiation field is calculated to prevent a worker from exceeding an allowable dose equivalent, it is called "stay time". Stay time is calculated as follows:

$$y\,Time = \frac{H_{allowable} - H_{recei}}{dose\ equivalent\ r}$$

where:

$H_{allowable}$ = *maximum allowable dose equivalent*
$H_{received}$ = *dose equivalent already accumulated*

Sample Problem 1.11-6

A worker must enter a 2.5 R/hr gamma radiation field to perform work as part of a team working on a radioactive effluent tank. His accumulated dose equivalent for the month is 120 mrem. If the monthly ALARA guideline is 600 mrem, what is his stay time in the area?

Sample Problem 1.11-7

An individual must enter a mixed gamma/neutron radiation field for emergency repair work. The radiation field consists of 2,500 mR/hr gamma, and 500 mrad/hr thermal neutron. Assuming the individual has received 340 mrem of his allowable 600 mrem for the month, what is the maximum stay time allowed?

Sample Problem 1.11-8

Assume the work in the previous example must take 35 min. to be completed, and a group of workers, with no previous exposure for the month, is available. How many additional workers (in addition to the first worker in Example 1.11-7) are needed to complete the emergency task if no one individual exceeds the ALARA monthly guideline?

DISTANCE

1.11.06 Identify "distance to radiation sources" techniques for minimizing personnel external exposures.

The intensity of the radiation field decreases as the distance from the source increases. Therefore, increasing the distance will reduce the amount of exposure received. *In many cases, especially when working with point sources, increasing the distance from the source is more effective than decreasing the time spent in the radiation field.*

Theoretically, a point source is an imaginary point in space from which all the radiation is assumed to be emanating. While this kind of source is not real (all real sources have dimensions), any geometrically small source of radiation behaves as a point source when one is more than a few source dimensions away. Radiation from a source is emitted equally in all directions. Thus, the photons spread out to cover a greater area as the distance from the point source increases. The effect is analogous to the way light spreads out as we move away from a single source of light such as a light bulb.

The radiation intensity for a point source decreases according to the **Inverse Square Law** which states that as the distance from a point source changes the dose rate decreases or increases by the square of the ratio of the distances from the source. The inverse square law becomes inaccurate close to the source (i.e., about 10 times the diameter of the source).

Calculations to show the relationship will be used later in this section.

Various techniques are employed to accomplish external exposure reduction by increasing the distance:

Remote handling tools/remote control devices

Tools, such as tongs or long-handled tools, are an effective means of increasing the distance from a point source to a worker. For very high radiation fields, remote control devices may be appropriate, especially if the task is performed frequently.

Remote observation by cameras or indicators

Gauges or meters can be moved to a location remote from the source of radiation. Closed-circuit television and video cameras can be used to allow observation of work activities or system operations from a location remote to the source of radiation.

Move work to another location

If the source of radiation can not be reduced, then possibly the work can be moved to a low exposure area. For example, if a pump or valve needs reworking, then an exposure savings could be achieved by removing the component from the system and performing all repair work in a lower exposure area.

Maximize the distance

Maximize the distance during work from the source when possible. For workers or inspectors not actively engaged in the work activity in the radiation field, moving to a lower exposure rate "waiting" area can be effective. Identifying "low dose rate waiting areas" can notify workers of the location of the lowest exposure rate in an area or room. Be aware of the location of radiation sources at the worksite and locate the worker at a point farthest from the source. Work at arm's length and do not lie on or hug radioactive components.

Posting of areas

Posting of radiological areas based on radiation level is a method for increasing the distance between the workers and the radiation source.

Extendable instruments

Extendable radiation survey instruments, such as the Eberline Teletector, can reduce the exposure to the surveyor by increasing the distance.

POINT SOURCE CALCULATIONS

1.11.07 Using the point source equation (inverse square law), calculate the exposure rate or distance for a point source of radiation.

As previously mentioned, the exposure rate is inversely proportional to the square of the distance from the source. The mathematical equation is:

$$I_1(d_1)^2 = I_2(d_2)^2$$

where:

I_1 = exposure rate at 1st distance (d_1)

I_2 = exposure rate at 2nd distance (d_2)

d_1 = 1st (known) distance

d_2 = 2nd (unknown) distance

1) Assuming the attenuation of the radiation in the intervening space is negligible.

2) Assuming the dimensions of the source and the detector are small compared with the distance between them.

By algebraic manipulation, the equation can be used to determine the distance from a point source for a given exposure rate or the exposure rate at a given distance.

Sample Problem 1.11-9

A 1 Ci point source of Cs-137 has a gamma exposure rate of 3.38 R/hr at 1 ft. What would the exposure rate be at 3 ft?

Sample Problem 1.11-10

A 1 Ci point source of Co-60 has an exposure rate of 15.03 R/hr at 1 ft. At what distance would the exposure rate be 100 mR/hr?

The inverse square law holds true only for point sources; however, it gives a good approximation when the source dimensions are smaller than the distance from the source to the exposure point. Some sources, such as a pipe or tank, cannot be treated as a point source. These sources must be treated as line sources or large surface sources.

LINE SOURCE CALCULATIONS

1.11.08	*Using the line source equation, calculate the exposure rate or distance for a line source of radiation.*

The actual calculations for a line source involve calculus; however, the mathematics can be simplified if the line source is treated as a series of point sources placed side by side along the length of the source.

If the line source is treated in this manner, the relationship between distance and exposure rate can be written mathematically as:

$$I_1(d_1) = I_2(d_2)$$

i.e. the exposure rate is inversely proportional to the distance from the source.

1) Assuming the source material is distributed evenly along the line.
2) Assuming the point at which the exposure rate is calculated is on a line perpendicular to the center of the line source.
3) Assuming the width or diameter of the line is small compared to the length.
4) Valid to a point that is three times the longest dimension of the line source (3L), beyond which the point source formula should be used.

Sample Problem 1.11-11

A small diameter pipe containing radioactive resin has a length of 10 ft. The exposure rate at 1 foot is 5 R/hr. What is the exposure rate at 4 ft?

Sample Problem 1.11-12

What would the exposure rate be at 15 feet for the same small diameter pipe?

PLANAR OR SURFACE SOURCES

1.11.09 Identify how exposure rate varies depending on the distance from a surface (plane) source of radiation.

Planar or surface sources of radiation can be the floor or wall of a room, a large cylindrical or rectangular tank or any other type of geometry where the width or diameter is not small compared to the length. Accurate calculations for these types of sources require the use of calculus; however, a relationship can be described for how exposure rate varies with distance from the source.

When the distance to the plane source is small compared to the longest dimension, then the exposure rate falls off a little slower than 1/d (i.e. not as quickly as a line source).

As the distance from the plane source increases, then the exposure rate drops off at a rate approaching $1/d^2$.

The exposure rate versus distance calculations can be used to make an estimate of the radiation intensity at various distances. These estimates are valuable tools to estimate and verify the readings obtained from exposure rate meters.

MASS ATTENUATION COEFFICIENT

1.11.10 Identify the definition of "mass attenuation coefficient" and "linear attenuation coefficient".

The linear attenuation coefficient, μ, used in the photon attenuation equation is dependent on photon energy, chemical composition of the absorber (Z), and the physical density of the absorber. The linear attenuation is the probability of a photon interaction per path length and therefore has units of $(\text{length})^{-1}$ (typically cm^{-1}). When multiplied by length (as done in the exponent of e in the attenuation equation) the product is a unitless quantity as mathematically required for an exponent.

The linear attenuation coefficient will clearly change depending on the physical density of the absorber. It is desirable to express the probability of an interaction as a function of the amount of absorber encountered rather than the path length. This would be to represent the probability of an interaction by a value that is independent of density.

This is done by dividing the linear attenuation coefficient by the physical density, thus, "normalizing" the linear attenuation coefficient to the density of the material. The mass attenuation coefficient is the quantity obtained by dividing the linear attenuation coefficient by the physical density. Mathematically:

$$\boldsymbol{\mu_m = \mu_l/\rho}$$

where: μ_m = mass attenuation coefficient
μ_l = linear attenuation coefficient
ρ = physical density

When the units of the linear attenuation coefficient are cm^{-1} and the units of physical density are mg/cm^3 then the units of mass attenuation coefficient become cm^2/mg.

1.11.11	Identify the definition of "density thickness".
1.11.12	Identify the density-thickness values, in mg/cm^2, for the skin, lens of the eye and the whole body.

DENSITY-THICKNESS

The mass attenuation coefficient μ_m is used in the attenuation equation (from Lesson 1.07):

$$I = I_0 e^{-\mu x}$$

where: I = shielded (attenuated) radiation intensity
I_0 = unshielded radiation intensity
μ_m = mass attenuation coefficient
x = density-thickness value

When μ_m is used in the attenuation equation, x must have units of mg/cm^2 to cancel out the units of μ_m. With these units, x is called *density-thickness*. Density-thickness is a value equal to the product of the density of the absorbing material and its thickness. This value is given in units of mg/cm^2.

Recall that the density of any material is a measure of its mass per unit volume, as compared to the density of water. Water has a density of 1 g/cm^3, or 1000 mg/cm^3. According to ICRP 15, the density of soft human tissue is equal to 1000 mg/cm^3. Using this value we can calculate density-thickness values for various depths that radiation may penetrate into the human body and cause damage. For purposes of reporting radiation dose in accordance with 10 CFR 835, the tissue depths of concern are the skin (shallow dose), the lens of the eye, and the whole body (deep dose).

Table 1. Density-thickness Values for Human Body

Tissue	Depth	Density-thickness
Skin (shallow dose)	0.007 cm	7 mg/cm^2
Lens of the eye	0.3 cm	300 mg/cm^2
Whole body (deep dose)	1.0 cm	1000 mg/cm^2

The concept of "density-thickness" is important to discussions of radiation attenuation by human tissue, as well as detector shielding and windows, and dosimetry filters. Although materials may have different densities and thicknesses, if their density-thickness values are the same, they will attenuate radiation in a similar manner. For example, a piece of mylar used as a detector window with a density of 7 mg/cm^2 will attenuate radiation similarly to the skin of the human body.

These values can be used to design radiation detection instrumentation such that detector windows and shields have the same or similar density-thickness values. For example, some instruments use a detector window of 7 mg/cm^2. Any radiation passing the detector window would also penetrate to the basal layer of the skin on the human body and deposit energy in living tissue.

External dosimetry can be designed around these values such that dose equivalent is determined for the skin of the whole body, lens of the eye, and whole body. For example, a dosimeter filter may be designed as 1000 mg/cm^2. Any radiation passing this filter would also pass through the skin of the whole body and deposit energy in vital human organs.

SHIELDING CALCULATIONS

1.11.13 Calculate shielding thickness or exposure rates for gamma/x-ray radiation using the equations.

The simplest method for determining the effectiveness of the shielding material is using the concepts of half-value layers (HVL) and tenth-value layers (TVL).

One **half-value layer** is defined as the amount of shielding material required to reduce the radiation intensity to **one-half** of the unshielded value.

$$HVL = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$$

The symbol **μ** is known as the *linear attenuation coefficient* and is obtained from standard tables for various shielding materials.

One **tenth-value layer** is defined as the amount of shielding material required to reduce the radiation intensity to **one-tenth** of the unshielded value.

$$TVL = \frac{\ln(10)}{\mu} = \frac{2.3026}{\mu}$$

Both of these concepts are dependent on the energy of the photon radiation and a chart can be constructed to show the HVL and TVL values for photon energies.

Table 2. Half-Value Layers

Photon Energy (keV)	HVL (cm)			
	Lead (11.35 g/cm^3)	Iron (7.86 g/cm^3)	Concrete (2.4 g/cm^3)	Water (1.0 g/cm^3)
500	0.38	1.0	3.3	7.2
1000	0.86	1.5	4.5	9.8
1500	1.2	1.8	5.6	12.0
2000	1.3	2.1	6.4	14.0
3000	1.5	2.4	7.9	17.5

The basic calculational approach to photon shielding is to determine the existing exposure rate, decide on the desired exposure rate after shielding and then calculate how many HVL or TVL will be needed. The basic equation for using the HVL concept is:

$$I = I_0 \left(\frac{1}{2}\right)^n$$

where:

I = shielded exposure rate

I_o = unshielded exposure rate

$$\text{no. of HVLs} = \frac{\text{shield thickness (c}}{\text{HVL thickness (cm}}$$

The basic equation for using the TVL concept is:

$$I = I_0 \left(\frac{1}{10}\right)^n$$

where:

$$I = \textit{shielded exposure rate}$$

$$_0 = \textit{unshielded exposure rate}$$

$$\textit{no. of TVLs} = \frac{\textit{shield thickness}}{\textit{TVL thickness (c}}$$

Sample Problem 1.11-13

> Calculate the shielded exposure rate from a 500 mR/hr Cs-137 source with 5 cm of lead shielding. The HVL for Cs-137 and lead is 0.65 cm.

Sample Problem 1.11-14

Calculate the shielded exposure rate from a 7.4 R/hr Cs-137 source with 4 cm of lead shielding. The HVL for Cs-137 and lead is 0.65 cm.

Sample Problem 1.11-15

Calculate the #TVL and the thickness of lead required to reduce the exposure rate from a 7.5R/hr Co-60 source to less than 100 mR/hr. One TVL for Co-60 and lead is 4.0 cm.

Sample Problem 1.11-16

Calculate the #TVL and the thickness of lead required to reduce the exposure rate from a 450 mR/hr Co-60 source to less than 5 mR/hr. One TVL for Co-60 and lead is 4.0 cm.

SAMPLE PROBLEM ANSWERS:

1. 3.38 R/hr
2. 0.564 R/hr *or* 564 mR/hr
3. 1.715 R/hr
4. 0.25 Ci
5. 180 mR
6. 11.5 min
7. 3.9 min
8. 4 additional (each may stay maximum of 9 min)
9. 0.376 R/hr *or* 376 mR/hr
10. 12.26 ft
11. 1.25 R
12. 0.333 R *or* 333 mR at 15 ft
13. 2.4 mR/hr
14. 0.104 R/hr *or* 104 mR/hr
15. #TVL = 1.88; lead thickness = 7.5 cm
16. #TVL = 1.95; lead thickness = 7.8 cm

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